A Stepped Frequency CW SAR for Lightweight UAV Operation

Dr Keith Morrison
Department of Aerospace, Power and Sensors
University of Cranfield, Shrivenham
Swindon, SN6 8LA
UK

k.morrison@cranfield.ac.uk

ABSTRACT

A stepped-frequency continuous wave (SF-CW) synthetic aperture radar (SAR), with frequency-agile waveforms and real-time intelligent signal processing algorithms, is proposed for operation from a lightweight UAV platform. An SF-CW radar offers some distinct advantages over a pulsed radar. It measures the frequency response of the scene across a set of discrete frequencies over the bandwidth of interest, at each element position along the synthetic aperture. This means the individual frequency measurements are low power, but which are then integrated to simulate a much higher-power pulsed system. This is a cost effective way of providing radars with a low probability of interception (LPI), operating across wide frequency bands to obtain high image resolutions. In contrast, pulsed radars require large peak powers. Low power operation, and associated simple SF-CW circuitry, provides significant savings in the mass and size of the SAR sensor. The use of dedicated antennas avoids switching hardware and allows maximisation of each antenna's sensitivity for either transmit and receive purposes. To alleviate any bandwidth restrictions imposed by the spatial sampling requirements along the aperture, an approach is outlined using frequency randomised waveforms which allows the bandwidth to be greatly under-sampled before the appearance of significant sampling artefacts. This also provides benefits to the LPI performance of the radar. For a fixed transmit power, omission of frequencies naturally produces a decrease in target signal. However, an intelligent frequency selection scheme is proposed to alleviate signal drop-off, such that a thirty percent frequency thinning was found to produce only a 1dB drop in signal intensity.

1.0 INTRODUCTION

A stepped frequency continuous wave (SF-CW) synthetic aperture radar (SAR) offers some distinct advantages over a time-pulsed radar sensor for operation from a lightweight UAV reconnaissance platform. Pulsed radars are complex systems and require large peak powers. In contrast, a CW waveform allows use of the full dwell time between samples, that is, a duty-cycle ratio approaching 100%. The frequency response of the scene is measured across a set of discrete frequencies over the bandwidth of interest, at each element position along the synthetic aperture. This means the individual frequency measurements are low power, but which are then integrated to simulate a much higher power pulsed system. This also reduces the probability of interception of the radar by enemy listeners. The data are processed by pulse synthesis techniques using the relationship that the time domain pulse, P(t), is the Fourier relative, F, of the frequency data, f, P(t) ↔ F(f). Synthetic pulse processing allows great flexibility, as a great variety of equivalent P(t) waveforms can be realised by software processing different combinations and selections of the frequency data set.

A significant restriction to the use of SF-CW radars, however, arises from the requirement to sequentially sample each frequency across the bandwidth. The time available to do this is restricted by the need to meet

Morrison, K. (2005) A Stepped Frequency CW SAR for Lightweight UAV Operation. In *Advanced Sensor Payloads for UAV* (pp. 22-1 – 22-4). Meeting Proceedings RTO-MP-SET-092, Paper 22. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 MAY 2005	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
A Stepped Frequency CW SAR for Lightweight UAV Operation	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Aerospace, Power and Sensors University of Cranfield, Shrivenham Swindon, SN6 8LA UK**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM202032., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**34**	

the spatial sampling requirements along the array to avoid grating-lobe effects. This is particularly problematic for fast moving platforms or large image swaths. The radial extent of the image swath sets the frequency sampling resolution, Δf, required to avoid range ambiguities. The range resolution is given by the bandwidth, and is built up by monotonically increasing the frequency at the Δf step interval. For fast moving platforms, however, there may be insufficient time to gather in all the frequencies required to reach a desired resolution. To address this problem, an approach is proposed for an SF-CW SAR, which allows the bandwidth frequency spectrum to be greatly under-sampled without significant introduction of unwanted artefacts into the imagery.

2.0 MODELLING RESULTS

A model code was written to carry out simulations of the performance of a frequency-agile SF-CW SAR. Initial simulations were carried out using a fully-sampled frequency set. This consisted of a total of 101 frequencies over a bandwidth B=0.15GHz at a spacing Δf=1.5MHz, which provides for an unambiguous range of 100m. A SAR intensity image is shown in Figure 1 (left) for an 80m x 80m grid of 25 point targets at a slant range of 5km. The imaging scheme provides an equal resolution in range and cross-range of ~1.4m.

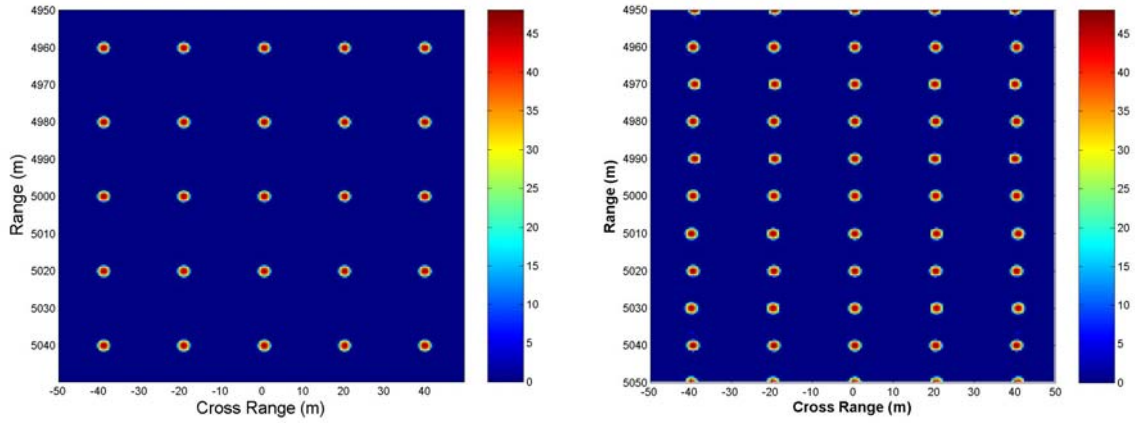


Figure 1: (Left) Range-unambiguous SAR image of a grid of 25 point scatterers over an 80m x 80m area using a full frequency set. The intensity range is 48dB. (Right) Using a simple linear re-sampling of the 101 frequencies used in Figure 1 to 51 frequencies, with an increased Δf=3.0MHz to cover the bandwidth The reduction of the unambiguous range to 50m has produced strong range-ambiguities.

It can be expected that under-sampling would produce unwanted image artefacts. This is the case shown in Figure 1 (right) for a 50 percent thinning, using a simple linear re-sampling of the 101 frequencies to 51 frequencies with an increased Δf=3.0MHz to cover the bandwidth. The reduction of the unambiguous range to 50m has produced strong range ambiguities. Further frequency thinning would be expected to produce increasingly undesirable image artefacts. However, randomization of the set of frequencies omitted from sweep to sweep - whilst maintaining a given bandwidth - allowed considerable thinning before the introduction of significant image artefacts. Figure 2 show images as for Figure 1, but with thinned frequency sets, omitting 50, 70 and 90 percent of the full frequency set. Figure 2 shows that the quality of the resulting image is hardly affected by frequency-thinning at 50 percent, with a target-to-maximum-sidelobe ratio better than 40dB, in strong contrast to Figure 1 (right). The 70 percent thinning shows a target-to-maximum-sidelobe ratio of ~30dB, and even with 90 percent of frequencies omitted, the ratio is better than 20dB. Randomization acts so as to destroy sidelobe coherence across successive aperture element samples that would otherwise build up with the repeating sequence [1,2,3]. Sidelobe power is instead spread across the image as low-level unstructured broadband noise.

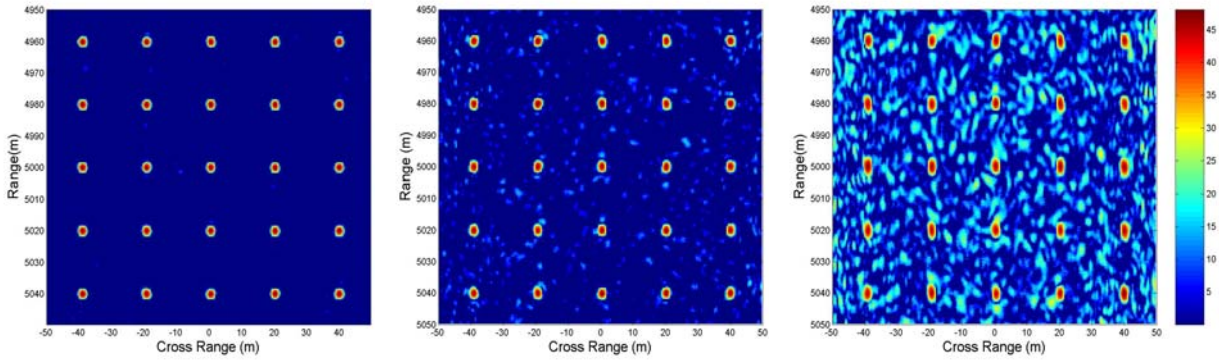


Figure 2: SAR image of a grid of 25 point scatterers over an 80m x 80m area, using a (left to right) 50, 70, and 90 percent thinned frequency set. The intensity range is 48dB.

The intensity of a target is the result of an integration across all frequencies. For a fixed transmit power, omission of increasing numbers of frequencies naturally produces a decrease in target signal. The energy received for a linear decrease in the number of frequencies for a thinning up to 95 percent can be expected to follow the drop-off shown by the solid line in Figure 3. A 30% and 70% thinning leads to a -3.2dB and -10.4dB drop, respectively. However, by use of a novel intelligent frequency selection scheme, signal intensity can be maintained well above this (dotted line). Adopting the scheme, the change in signal intensity for a 30 percent thinning is less than 1dB, and only -2.7dB and -5.7dB for a 50 and 70 percent thinning, respectively. There is a much increased fall-off rate as the frequency thinning approaches towards 100 percent.

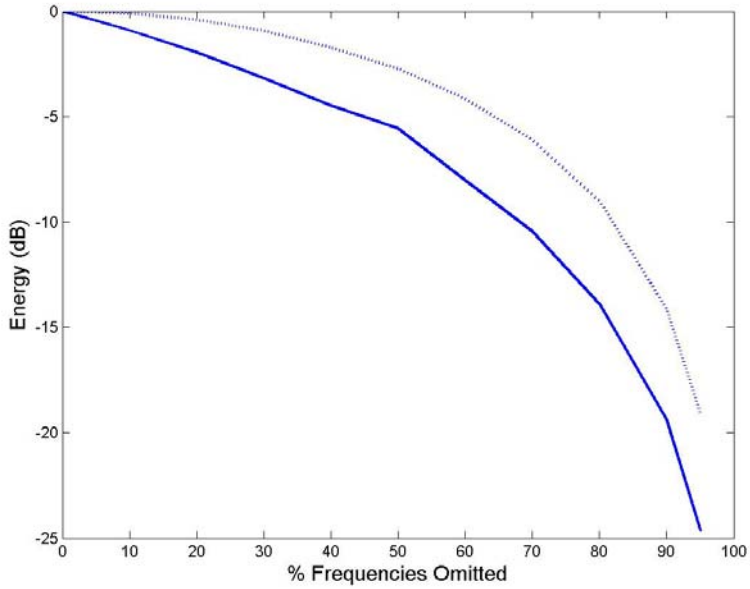


Figure 3: The decrease in target intensity with increasing frequency thinning for (solid line) randomly selected frequencies, and (dotted line) 'intelligently' chosen frequencies. The latter omission scheme leads to a fall-off rate significantly less than the drop-off that would otherwise be expected.

There is some degradation in range resolution as the frequency thinning becomes more extreme. Figure 4 shows the effect on the profile of a point target as the frequency spectrum is thinned to 50% and 70%. Whilst the 50% thinning shows a slight profile broadening, this is small compared to the resolution loss by use of the same number of frequencies in a fully sampled bandwidth.

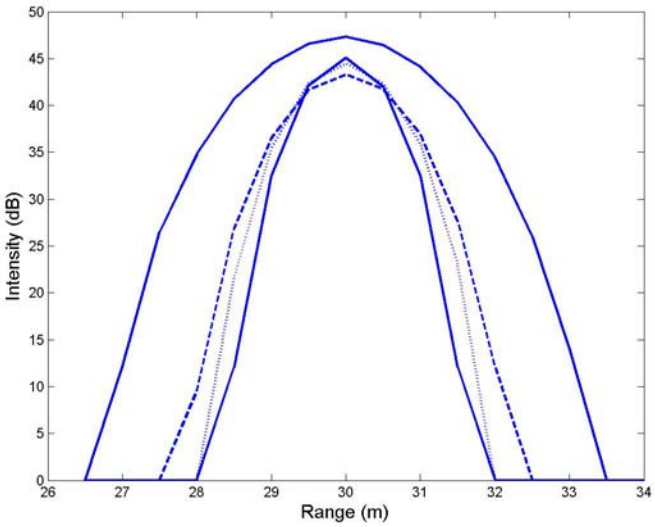


Figure 4: Range profile of a point target. (Solid line inner): full frequency set: (dotted line) randomized 50% thinning: (dashed line) randomized 70% thinning: (solid line outer) using 50% of the frequencies but over a fully sampled bandwidth.

3.0 CONCLUSION

The work has investigated a scheme of increasing the effective bandwidth for an SF-CW SAR, by the use of an under-sampled frequency set. Image artefacts caused by the under-sampling are significantly suppressed by the use of repeated randomization in the choice of omitted frequencies between sweeps at each element position along the aperture. In addition, an intelligent choice in the frequencies omitted can significantly maintain signal strength well above expected signal drop off.

4.0 REFERENCES

[1] Morrison, K., and Oldfield, L., 2002. *The Effect of Target Motion on ISAR Imagery.* In proceedings of Antenna Measurement Techniques Association, Cleveland, pp. 307-312.

[2] Morrison, K., 2004. *Recovery of Badly Motion-Degraded SAR Imagery by the use of Frequency-Randomized Waveforms*. Proceedings of IEEE 2004 RADAR Conference, Philadelphia, pp. 59-65.

[3] Flores, B.C., Jurgens, R.F., Chiu, R., 1994. *A Random Frequency Hop Code Technique for Improved Range-Doppler Imagery.* IEEE Antennas & Propagation Society Int. Symposium, Vol. 3, pp. 2010-2013.

The Royal Military College of Science

DEFENCE ACADEMY OF THE UNITED KINGDOM

Cranfield UNIVERSITY

Increasing the Effective Bandwidth of an SF-CW SAR using Frequency Agility

Keith Morrison

Department of Aerospace, Power & Sensors,
Cranfield University,
Royal Military College of Science,
Shrivenham,
Swindon SN6 8LA

Presentation

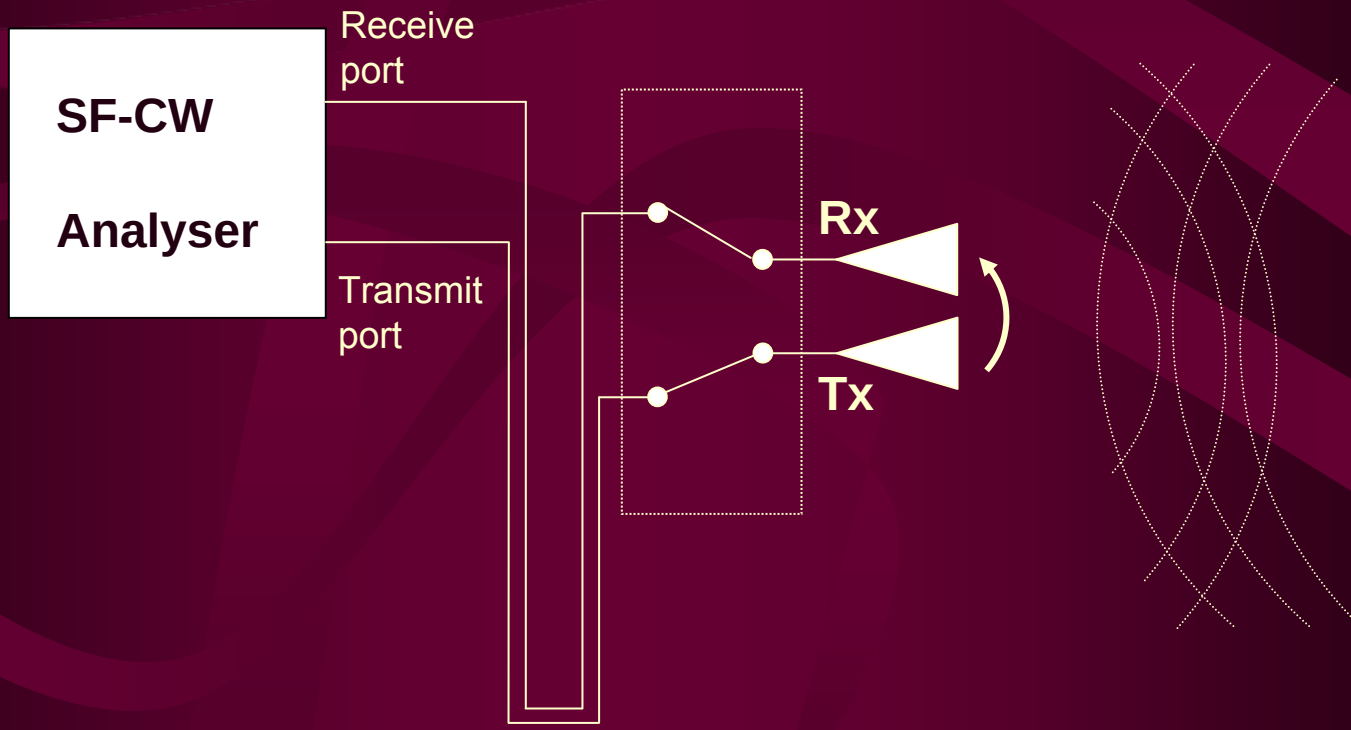
- Introduction to SF-CW radar
- Outline of ‘bandwidth increasing’ algorithm
- Algorithm performance evaluation for UAV operation

SAR UAV Requirements

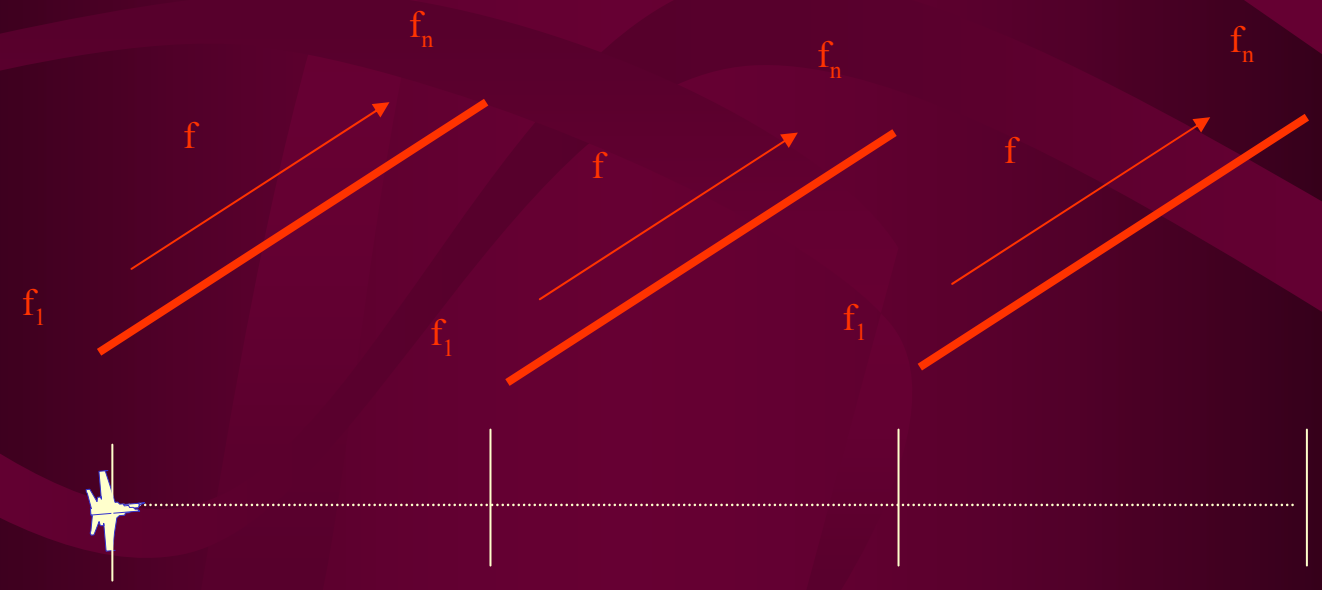
- Day & night, all weather capability
- Long range operation
- Rapid, large area search capability

- Flexible SAR system
- Affordable robust system for military platforms

CW Radar Concept



SF-CW Data Collection

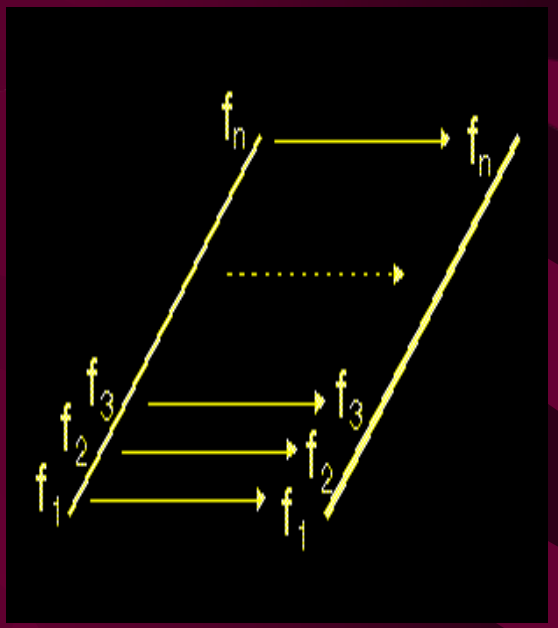


Frequency Domain Pulse Synthesis

P(t), is the Fourier relative, F, of the frequency data, f,
$P(t) \leftrightarrow F(f)$.

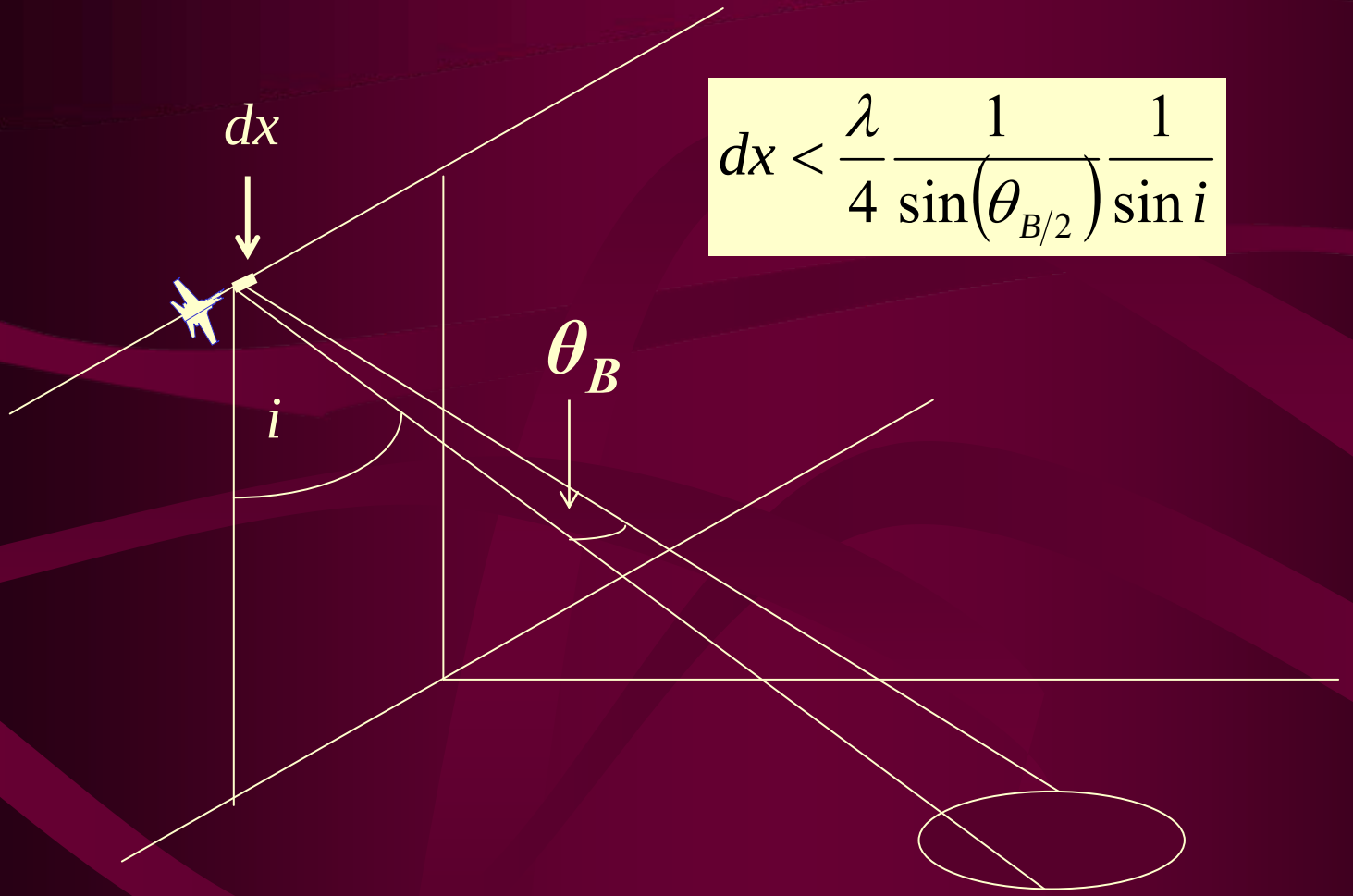
Time pulse is the summation of a set of frequencies over a bandwidth

- Bandwidth set by resolution requirement.
- Δf spacing across bandwidth set by swath width.
- B and Δf set number & density of frequency points.

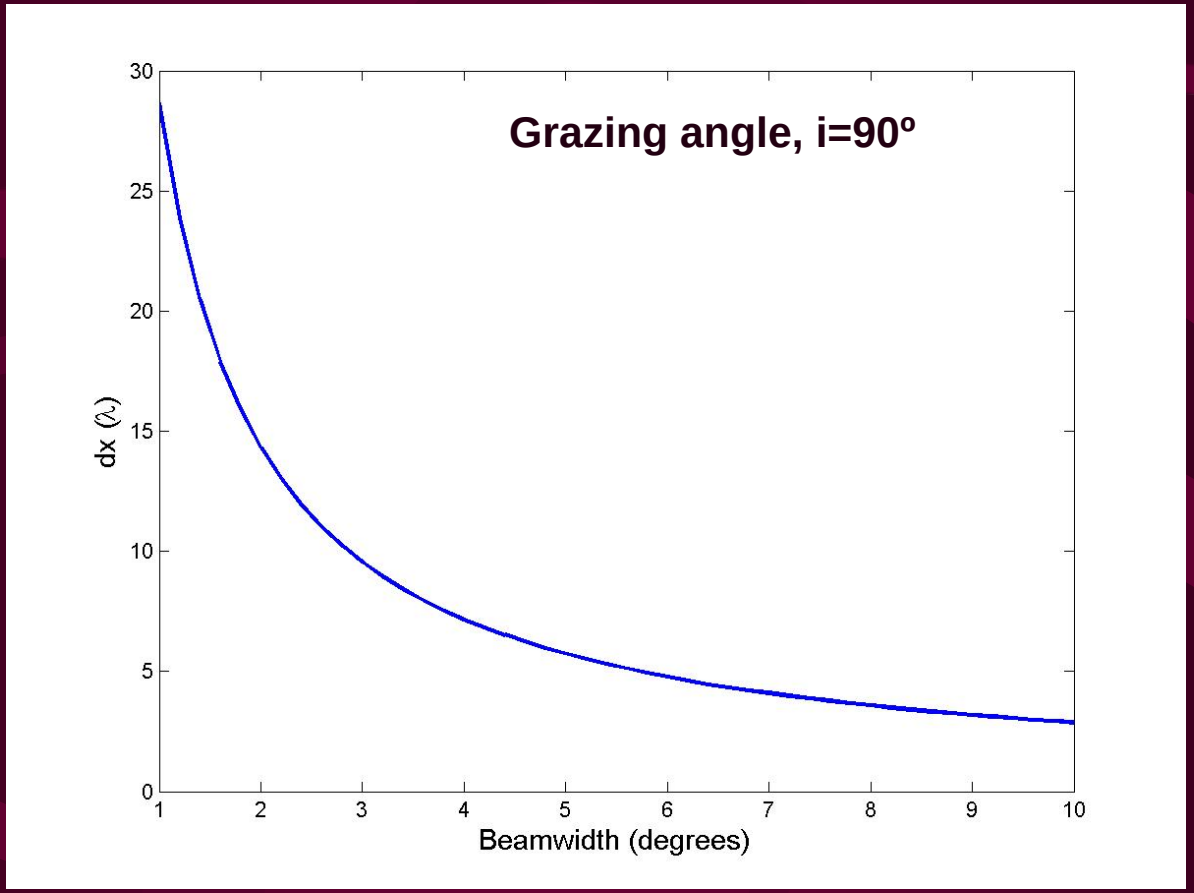


CW Radar Benefits

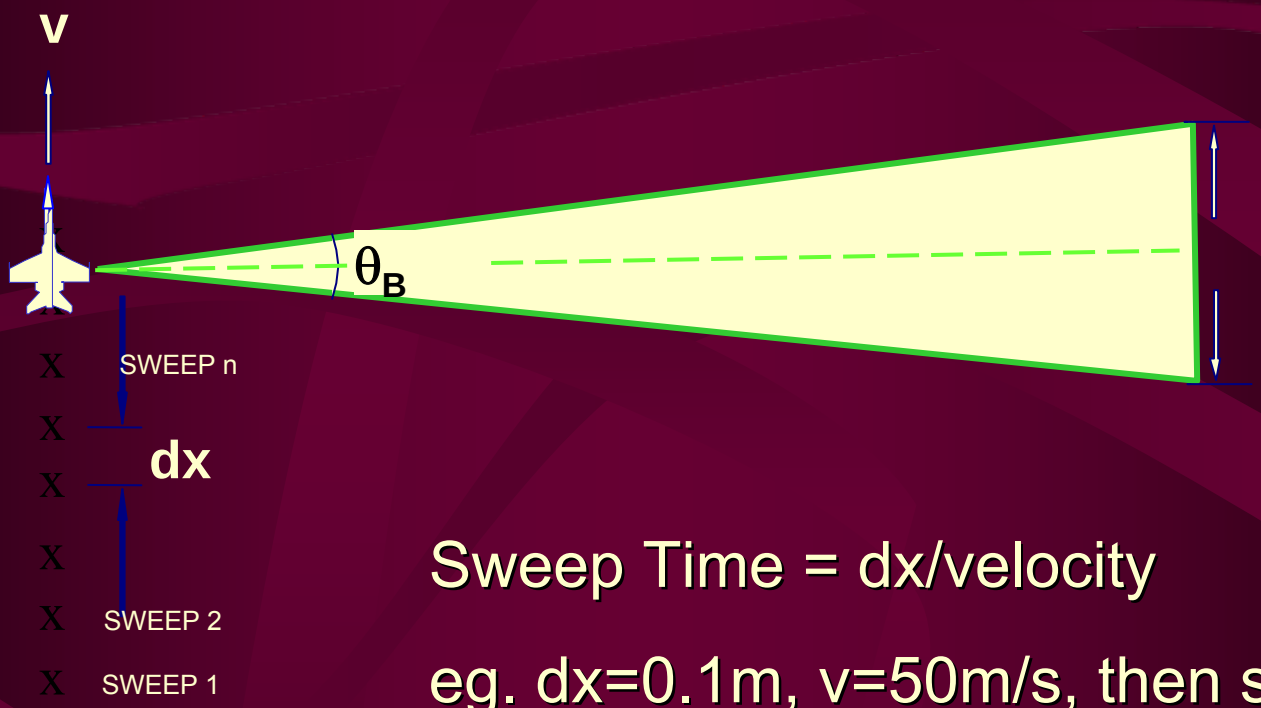
- low transmitted power
- reduced circuit complexity
- efficient duty cycle
- waveform versatility
- cost effectiveness
- low weight and volume requirements
- low probability of interception



$$dx < \frac{\lambda}{4} \frac{1}{\sin\left(\theta_{B/2}\right)} \frac{1}{\sin i}$$


Grazing angle, i=90º
dx (λ)
Beamwidth (degrees)
0
5
10
15
20
25
30
1
2
3
4
5
6
7
8
9
10

Aperture Sampling Restriction



Sweep Time = dx/velocity

eg. dx=0.1m, v=50m/s, then sweep time is 2ms.

Sweep time Σt_f .

For 300m swath $\rightarrow$ 2μs

Would have time to sample to 1000 frequencies

Transmit time, t_f , on a single frequency controlled by width of swath.

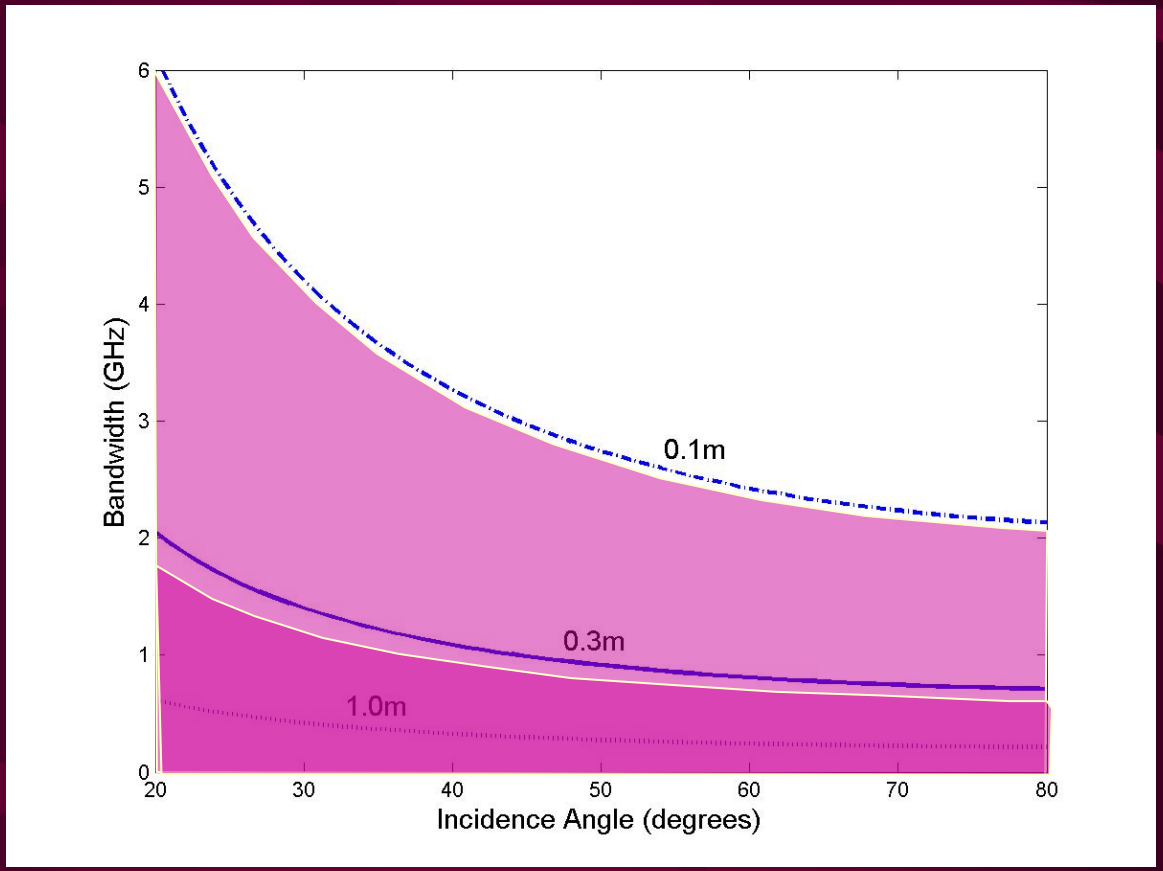
Sampling Considerations – 10GHz, 35m/s

v=35m/s

Beamwidth=3º

v=35m/s

Beamwidth=10º



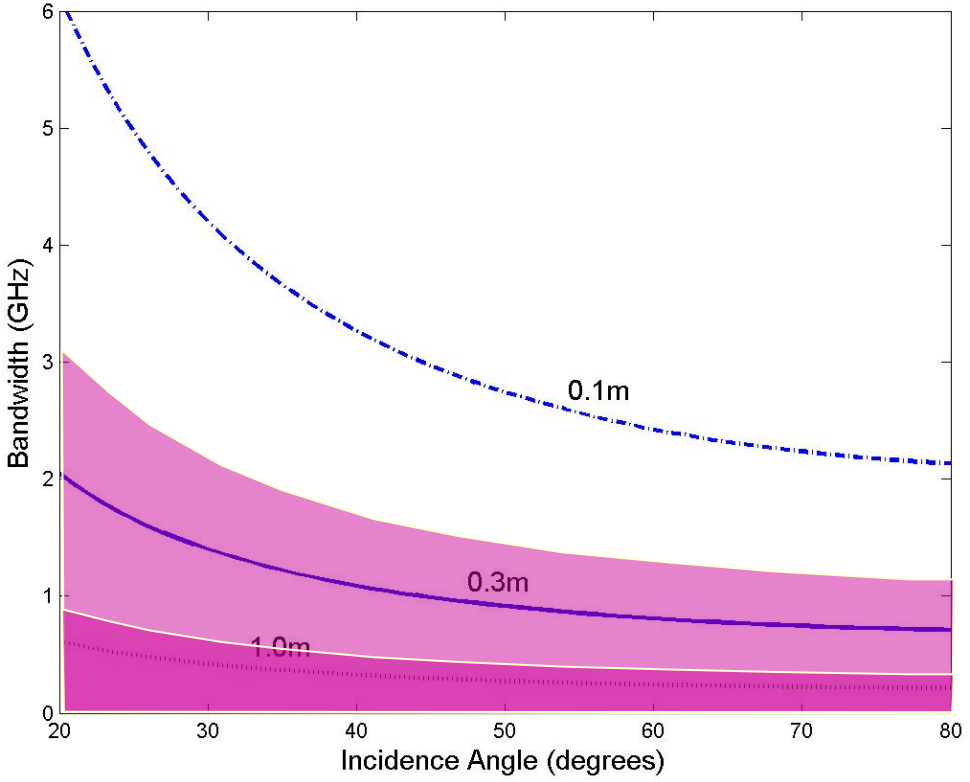
Sampling Considerations - 10GHz, 70m/s

v=70m/s

Beamwidth=3º

v=70m/s

Beamwidth=10º



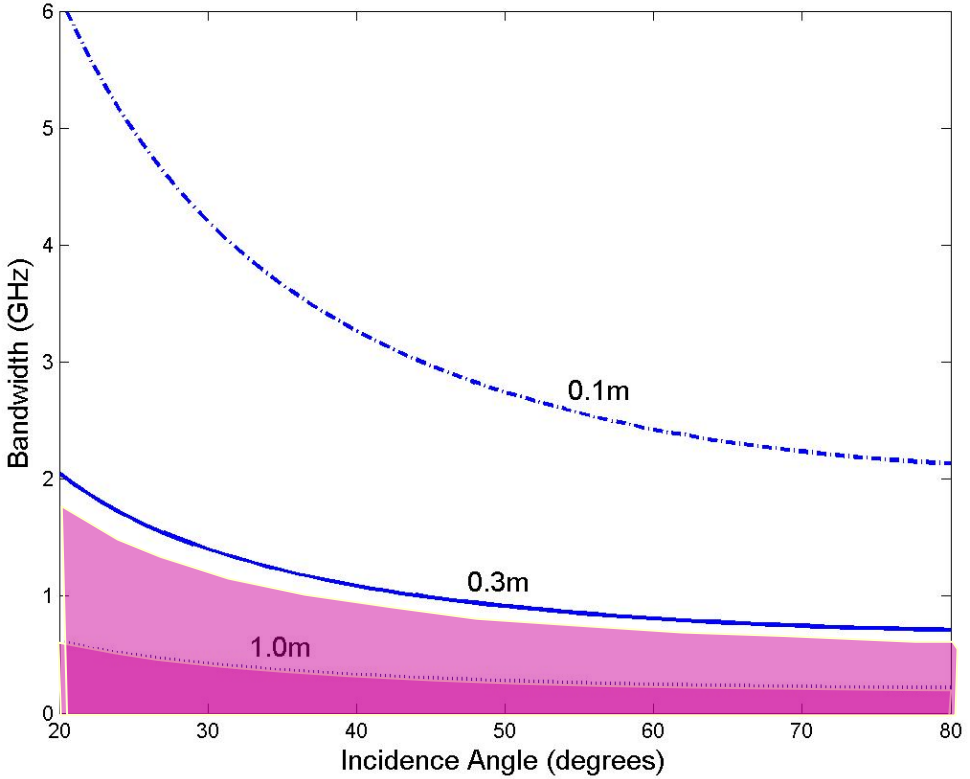
Sampling Considerations – 35GHz, 35m/s

v=35m/s

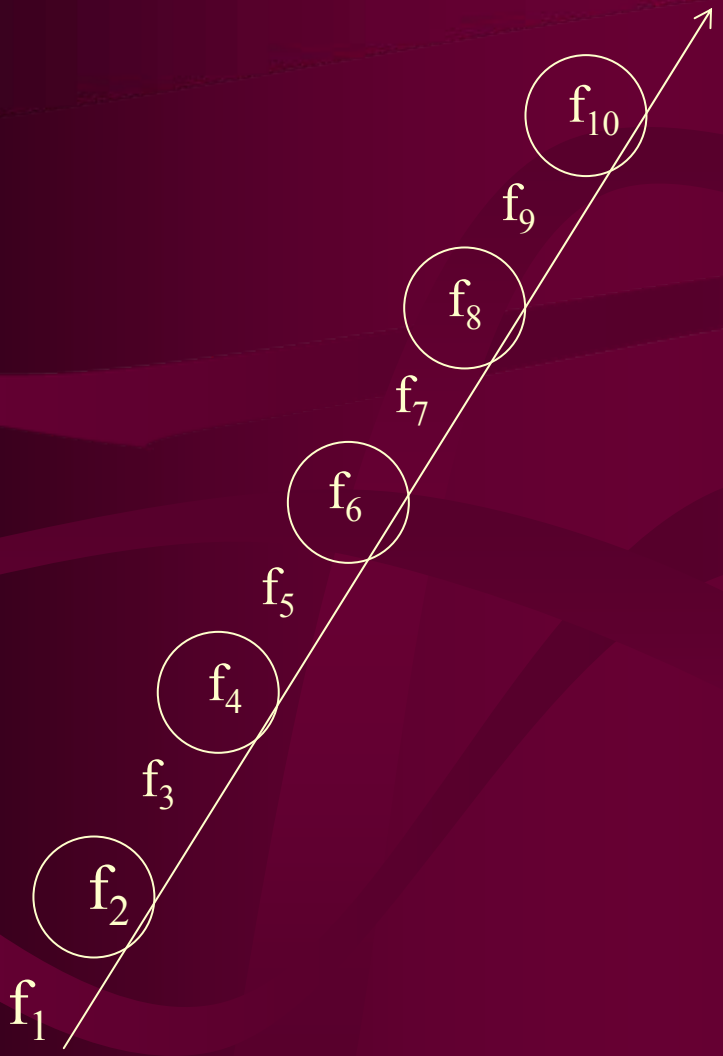
Beamwidth=3º

v=35m/s

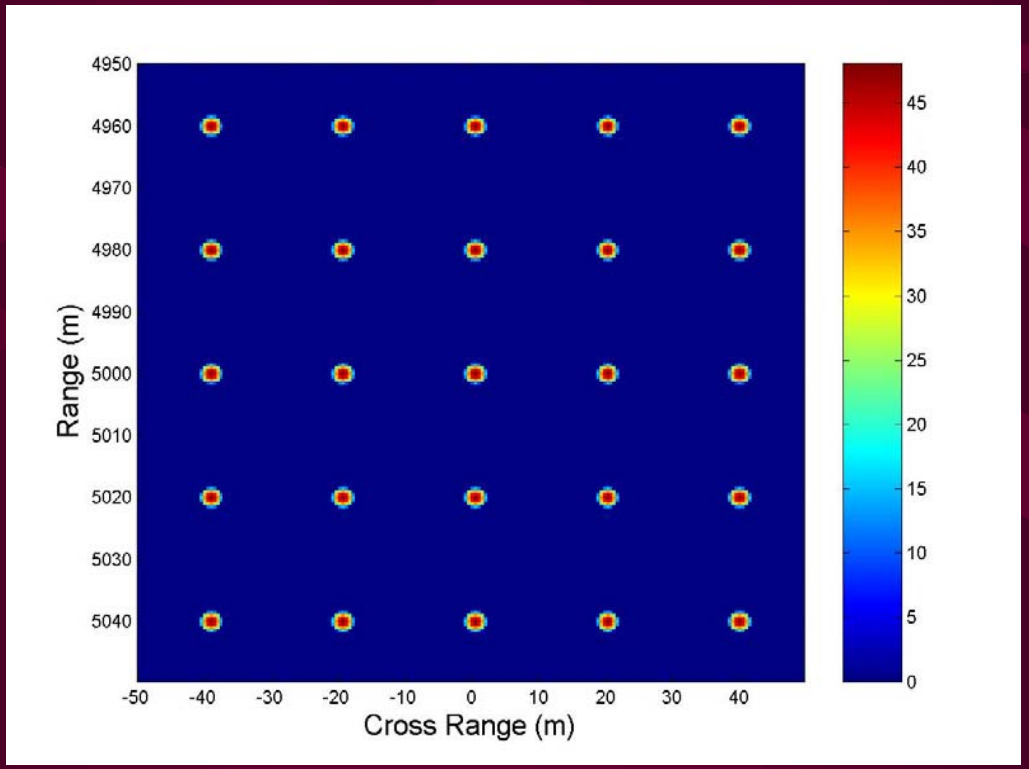
Beamwidth=10º

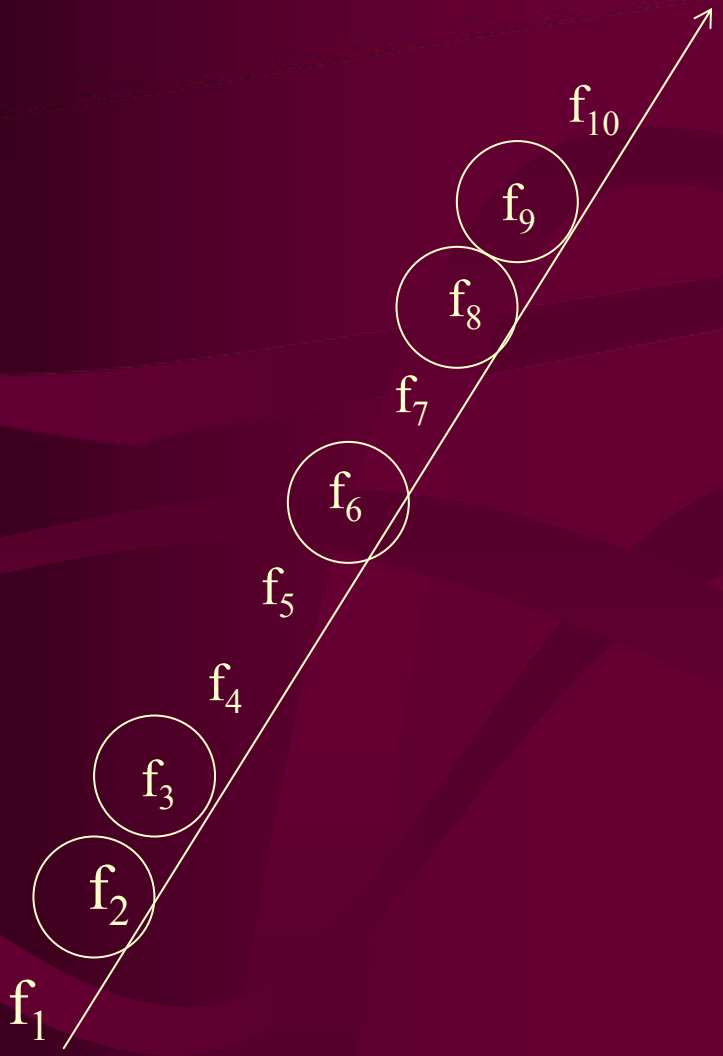


To address this issue, an approach is outlined which allows the frequency spectrum to be greatly under-sampled to provide a greater effective bandwidth.


f1
f2
f3
f4
f5
f6
f7
f8
f9
f10

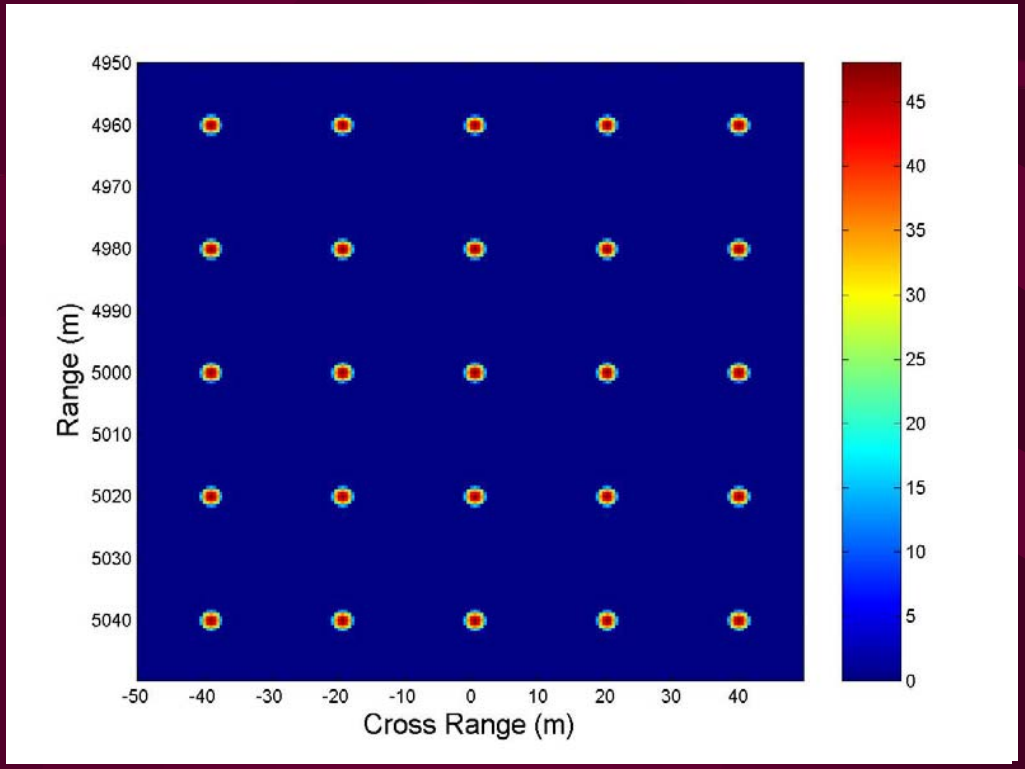
Frequency Thinning




f1
f2
f3
f4
f5
f6
f7
f8
f9
f10

Frequency Thinning

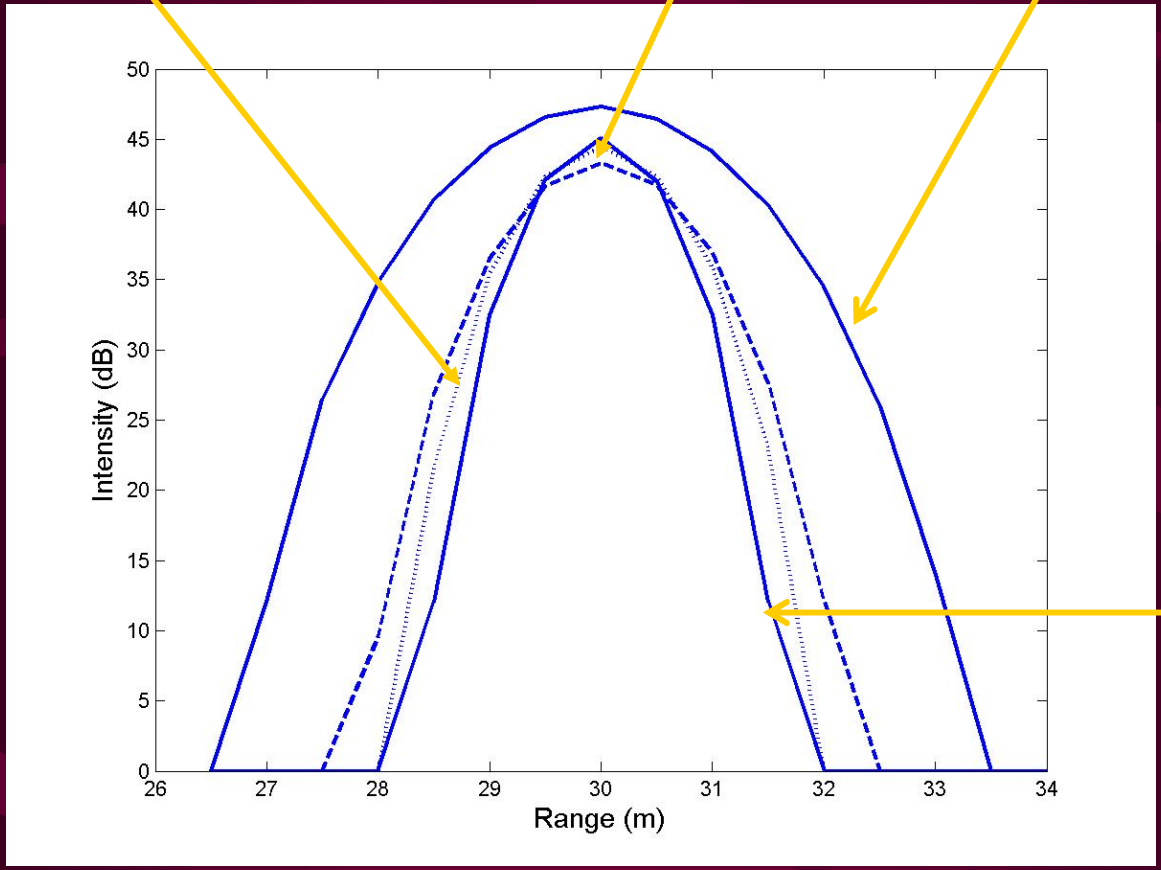
50% Thinning



50% Undersampled Full Bandwidth

70% Undersampled Full Bandwidth

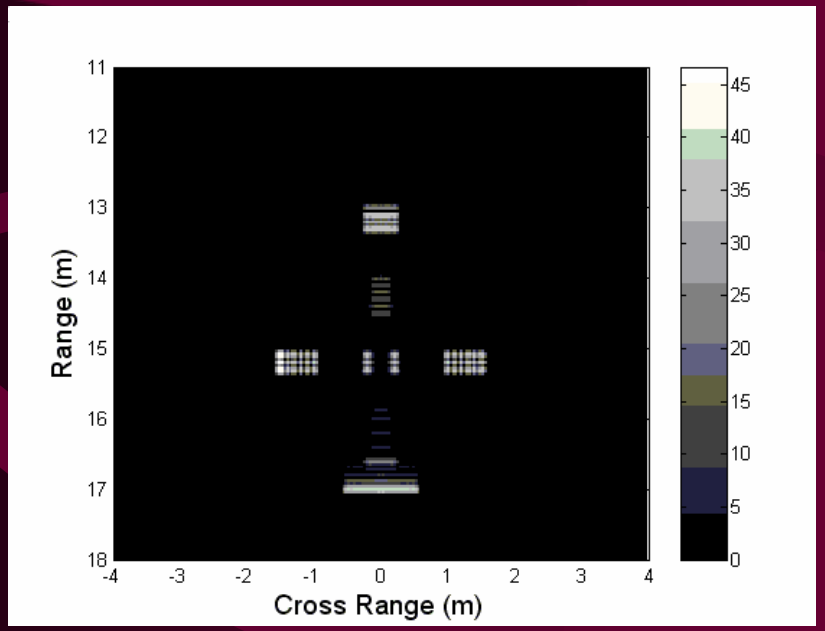
Fully Sampled 50% Bandwidth



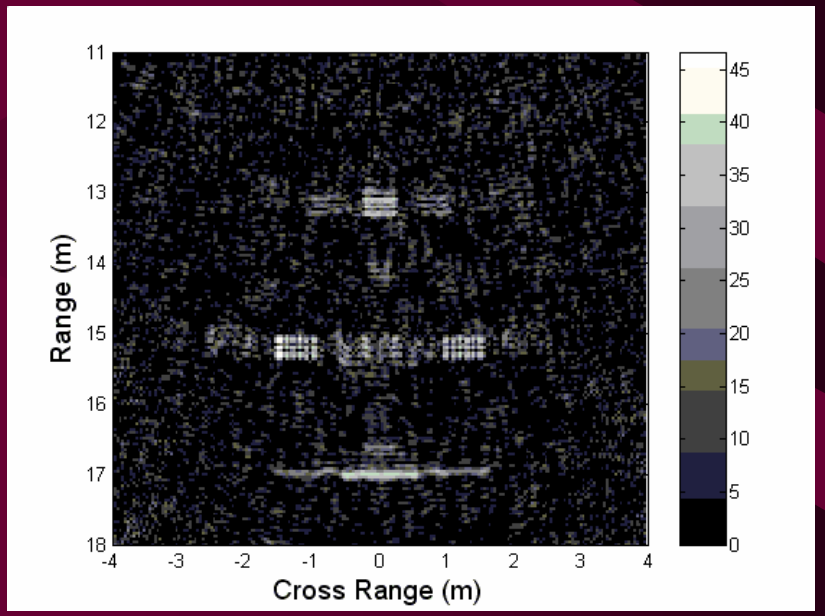
Fully Sampled

Previous Work

Monotonically Frequency Stepped Waveform



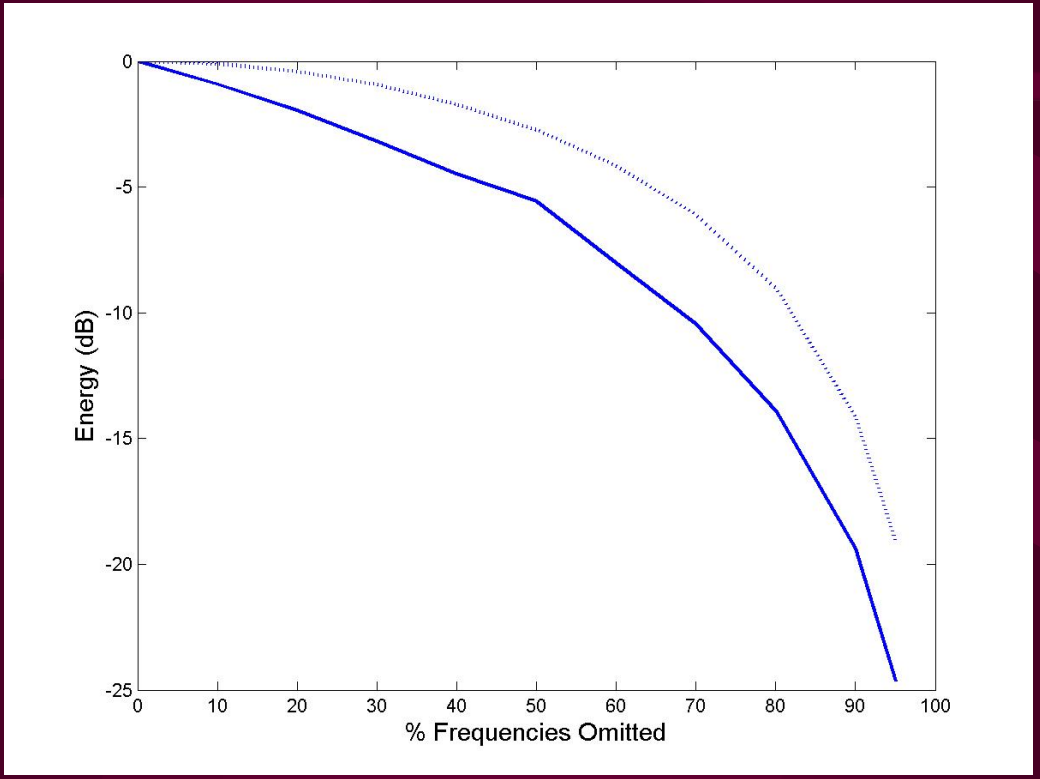
Frequency Randomised Waveform

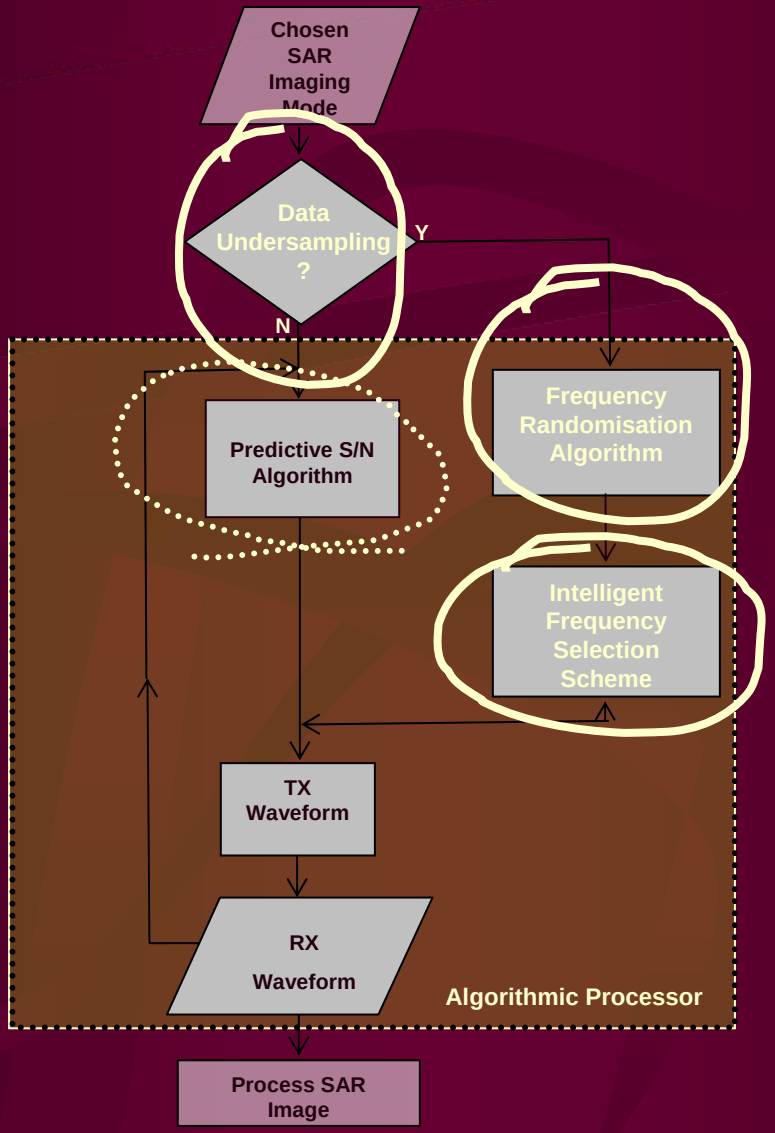


Capability Benefits

- flexible waveform choices
- not tied into fixed ‘PRF’ selections
- flexible mission scenarios
- image zoom capability
- ‘real-time’ adaptive capability

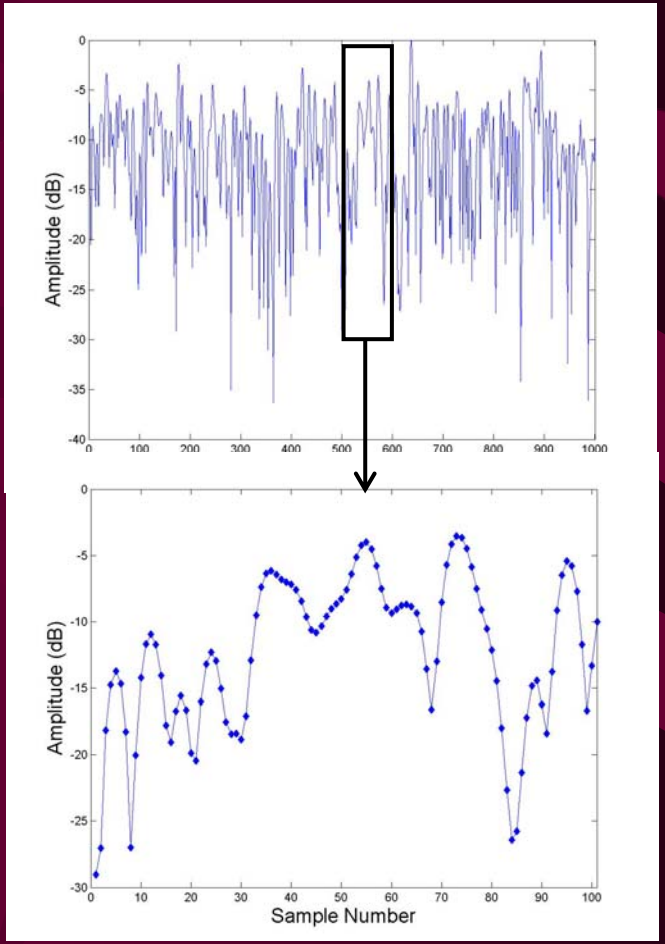
Intelligent Frequency Selection




Chosen SAR Imaging Mode
Data Undersampling ?
Y
N
Predictive S/N Algorithm
Frequency Randomisation Algorithm
Intelligent Frequency Selection Scheme
TX Waveform
RX Waveform
Algorithmic Processor
Process SAR Image

Predictive S/N Maximization

Algorithm proposed that will maximise the image signal-to-noise by means of an intelligent, real-time, adaptive distribution of power across the frequency domain using a predictive code which is a response to the reflectivity of the imaged scene.



Summary

UAV SAR concept which:

1. Allows the bandwidth of a SAR to be increased by making the imaging process tolerant to significant under-sampling.
2. flexible waveform choices
3. flexible mission scenarios
4. Intelligent adaptive waveform scheme for signal optimization
5. novel and innovative solution

Future Work

- Interpolation
- Frequency Randomization
- Grating-lobe steering
- Frequency selection
- Experimental validation & investigation

The GB-SAR System

END